New method for precise determination of top quark mass at LHC

Sayaka Kawabata
(Tohoku University)

in collaboration with Y. Shimizu (Kogakuin Univ.)
Y. Sumino (Tohoku Univ.)
H. Yokoya (KIAS)

Phys. Lett. B 741 (2015) 232-238

Outline

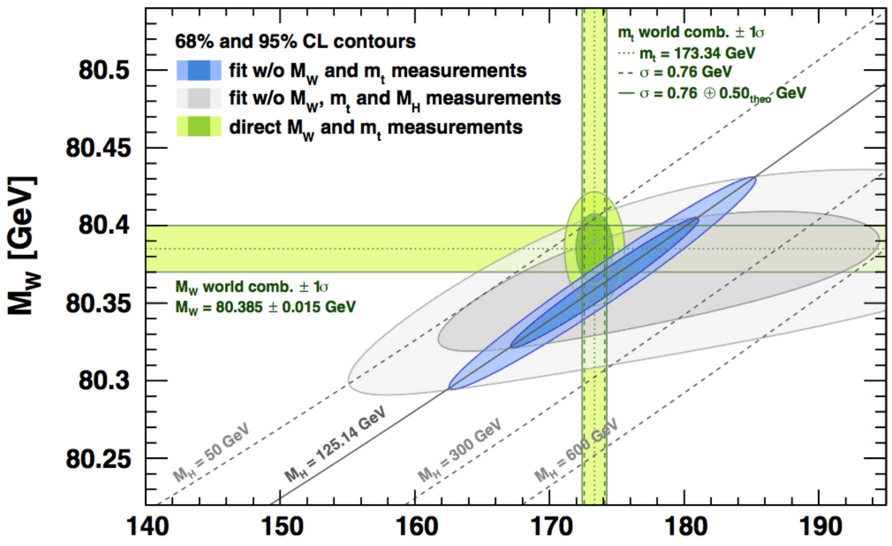
1. Introduction
2. Weight function method
3. Simulation analysis of top mass measurement with the weight function method
4. Summary and future work

1. Introduction

Motivation to measure the top quark mass

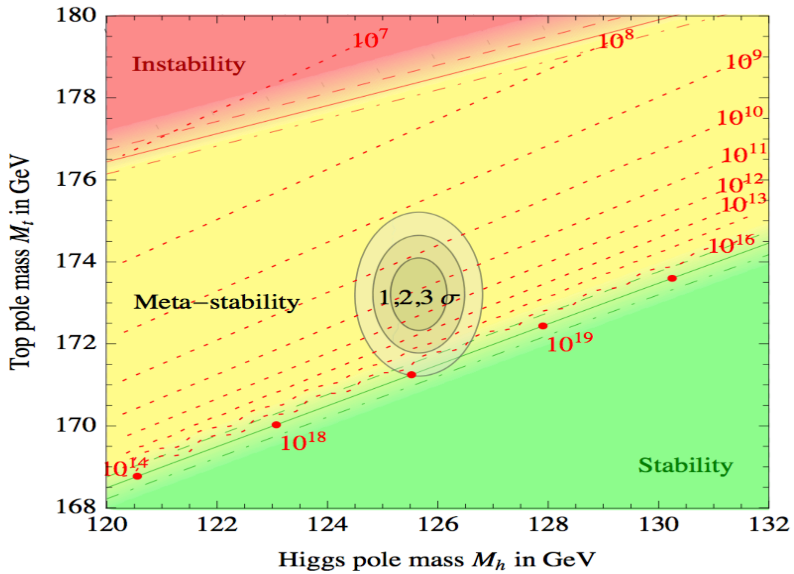
- One of the fundamental parameters of the SM
- Top mass is an important input parameter to various physics

★ EW precision tests for SM



Gfitter Group '14

★ SM vacuum stability



Buttazzo et al. '13

★ Beyond SM

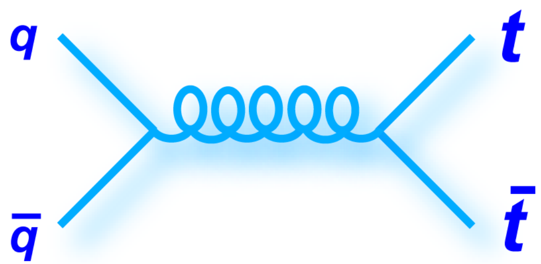
Top quarks at Tevatron and LHC

Tevatron

- $p\bar{p}$ collider
- discovered the top quark in 1995
- shut down in 2011

Main production process
: $t\bar{t}$ pair production

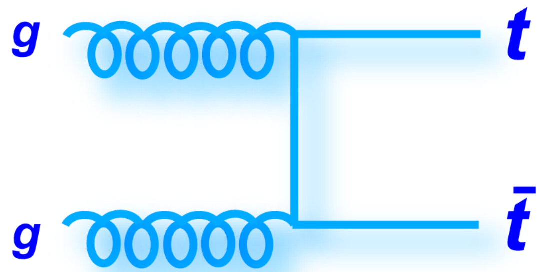
$\sigma(t\bar{t}) \sim 8\text{pb}$

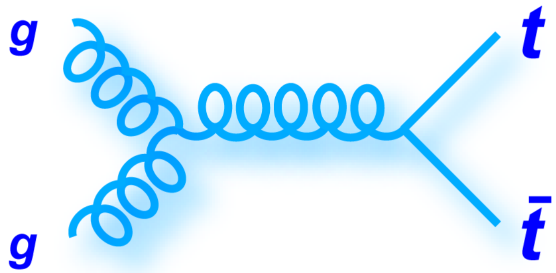


LHC

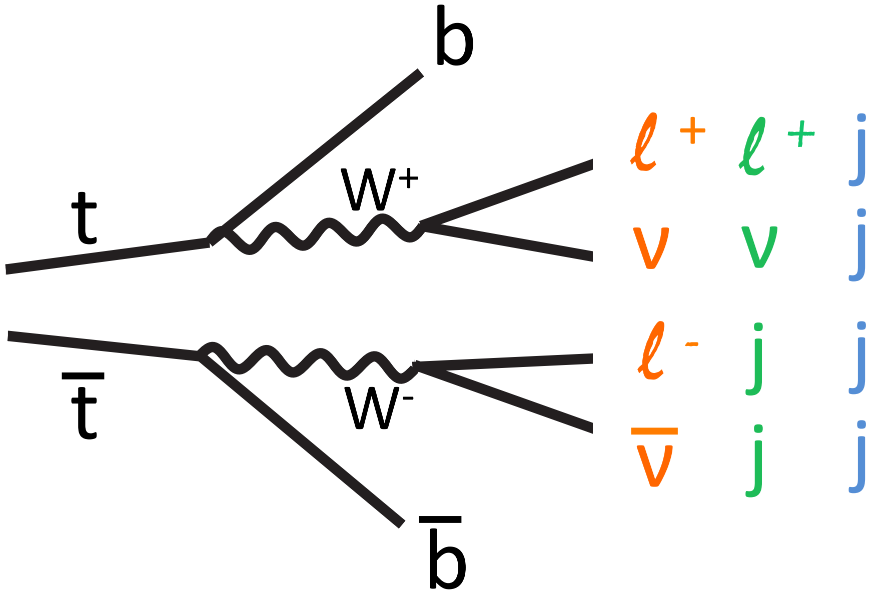
- pp collider
- ended data taking at $\sqrt{s}$ = 7, 8 TeV
- restart in 2015 at $\sqrt{s}$ = 13-14 TeV
  (yesterday!)

$\sigma(t\bar{t}) \sim 900\text{pb}$
($\sqrt{s}$ = 14 TeV)

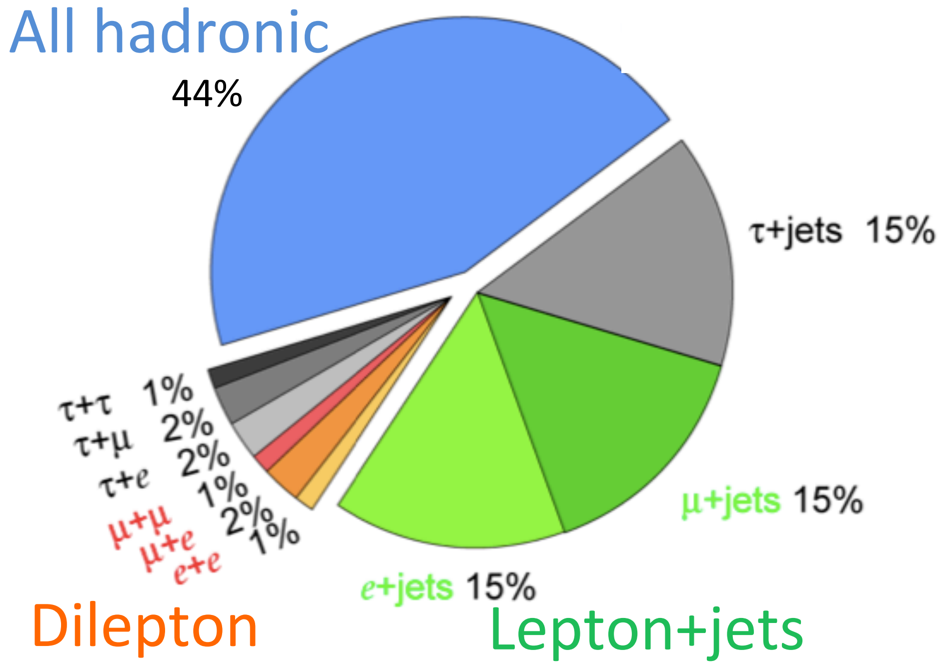




$t\bar{t}$ decay channel



$t\bar{t}$ branching ratio

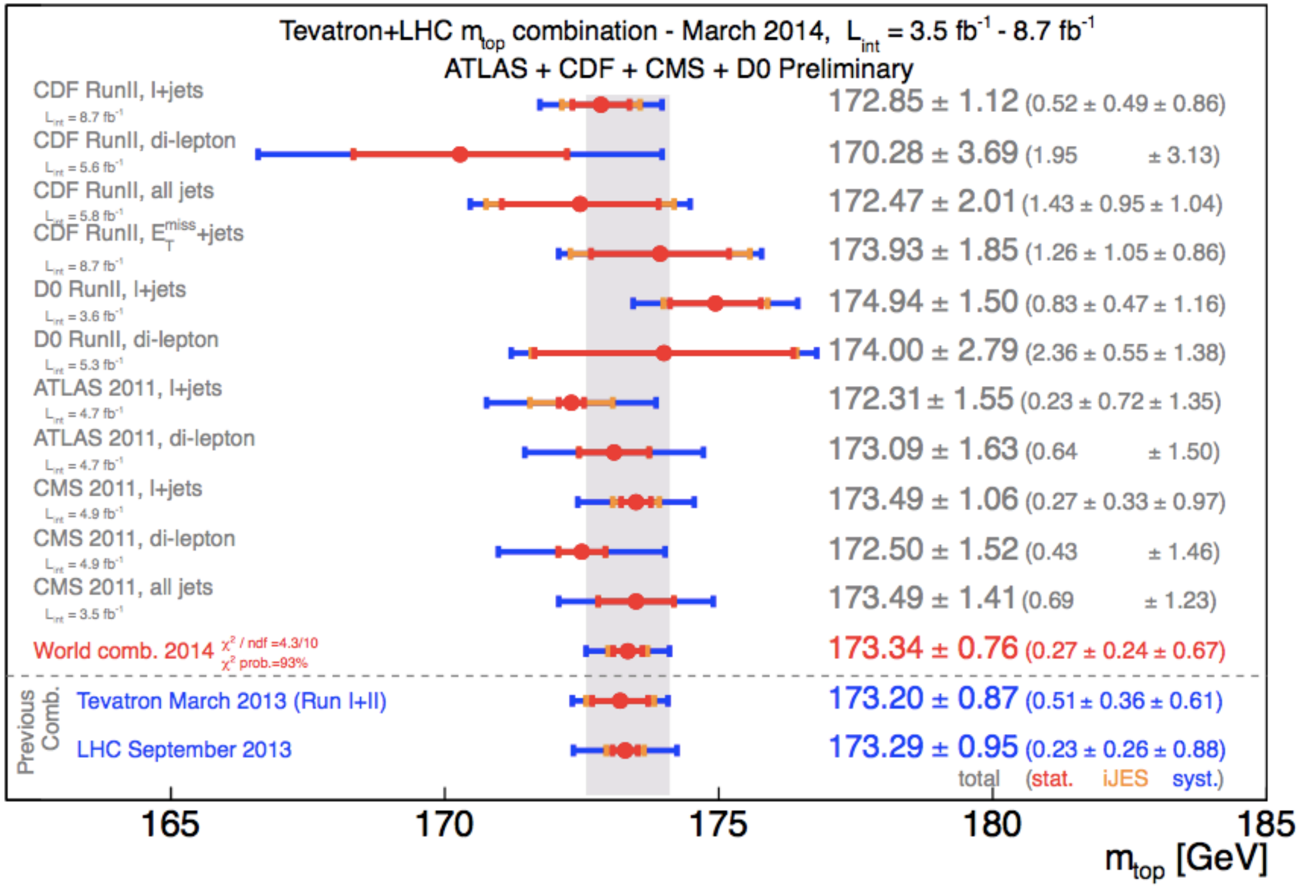


	Cross section	S / N
Dilepton	Small	Very good
Lepton+jets	Medium	Good
All hadronic	Large	Not good

Current status of top mass measurements

(direct measurement)

- Tevatron+LHC m_t combination (arXiv:1403.4427)



0.4% precision!

- Tevatron combination (arXiv:1407.2682) m_t = 174.34 ± 0.64 GeV
- CMS combination (Sep. 2014) m_t = 172.38 ± 0.65 GeV

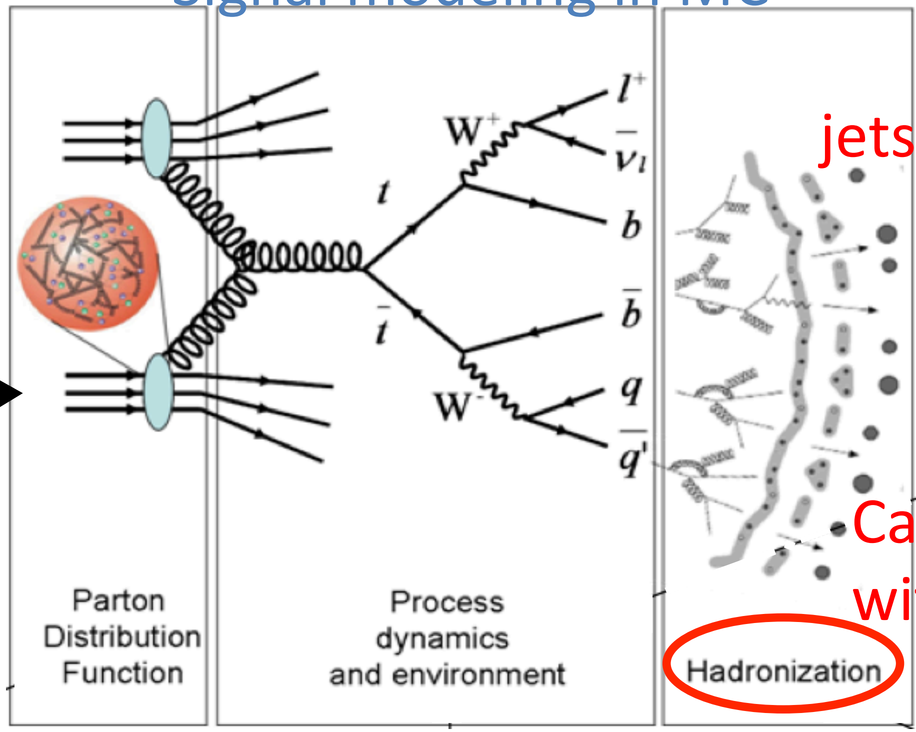
Measured mass : m_t^{MC}

Signal modeling in MC

Experiment

↕ m_t measurement

Theory (MC) - - - →



jets

Cannot be treated within pert. QCD

The measured mass is hadronization-model dependent (m_t^{MC})

$m_t^{MC} \neq m_t^{pole}$

Cannot evaluate the difference between m_t^{MC} and m_t^{pole}

Top quark mass?

- m_t^{MC} : Not a parameter defined in perturbative theory

- m_t^{pole} : Top quark has a color, so the physical on-shell quark cannot exist

  ⇨ Far from a fundamental param.

$$\frac{1}{\not{p} - m_0 - \Sigma(p, m_0)} = \frac{c}{\not{p} - m}$$

$$m = m(\mu)\Big(1 + \alpha_s(\mu)d^1 + \alpha_s^2(\mu)d^2 + \ldots\Big)$$

- $m_t^{\overline{MS}}$: Short-distance mass
  Free from IR contamination

$$m_0 = m(\mu)\Big(1 + \frac{\alpha_s}{\pi}\Big[\frac{1}{\epsilon}\Big]\Big)$$

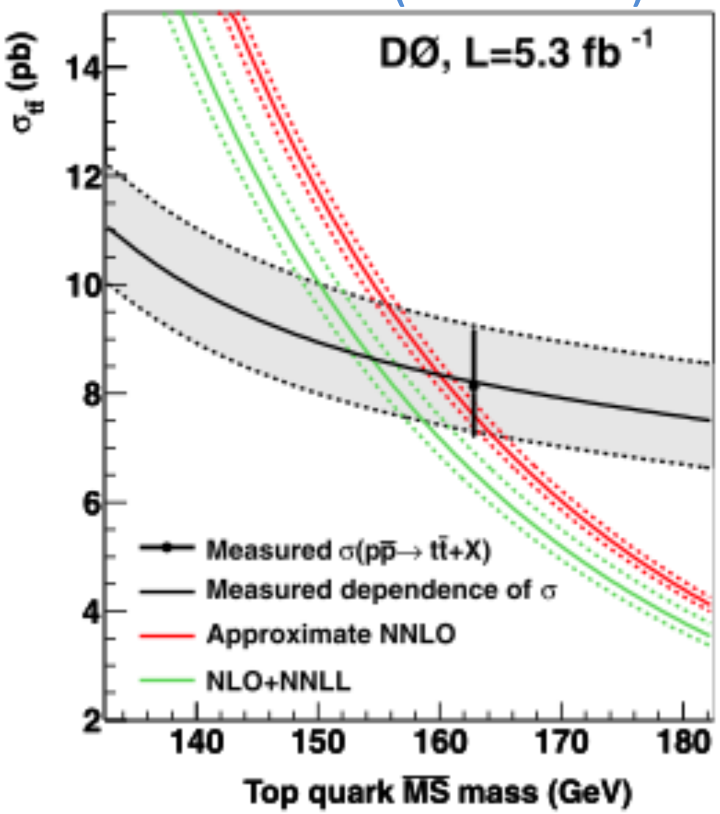
⇨ Known as a good parameter in pert. QCD

Important to determine $m_t^{\overline{MS}}$ accurately

Measurement of $\overline{\text{MS}}$ mass (and pole mass)

(from $t\bar{t}$ cross section)

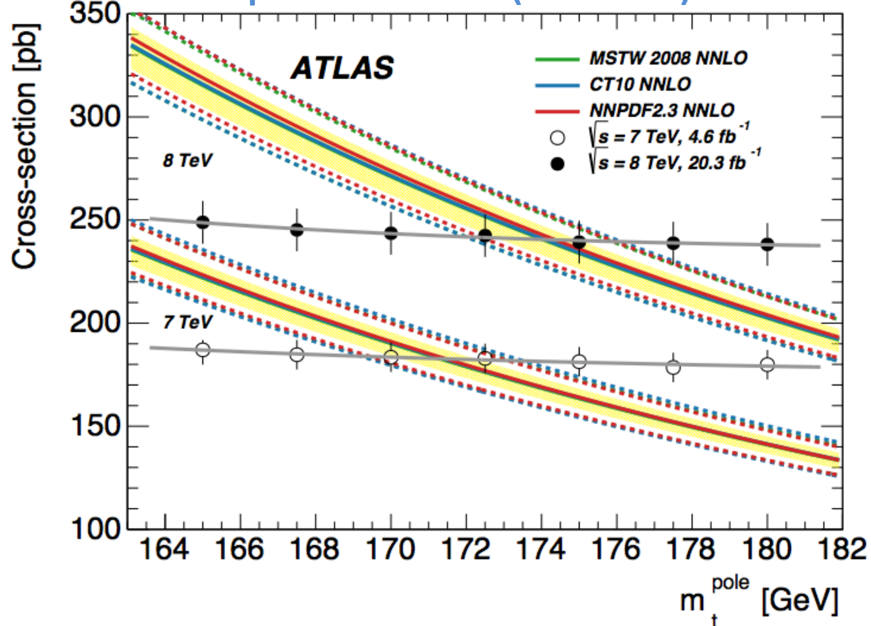
$\overline{\text{MS}}$ mass (Tevatron)



$$m_t^{\overline{\text{MS}}} = 160.0^{+5.1}_{-4.5}\ \text{GeV}$$

$$m_t^{\overline{\text{MS}}} = 154.5^{+5.2}_{-4.5}\ \text{GeV}$$

pole mass (ATLAS)



$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

The errors are still large.

- The sensitivity of $\sigma_{t\bar{t}}$ to m_t is not so strong
- Theoretical uncertainties $\sim$ 1.5 - 2 GeV

Aim of this study

Determine a theoretically well-defined top mass accurately at the LHC

m_t^{pole}, $m_t^{\overline{MS}}$

We propose a new method which uses lepton energy distribution

"Weight function method"

By a simulation analysis at LO, we show that this method works well.

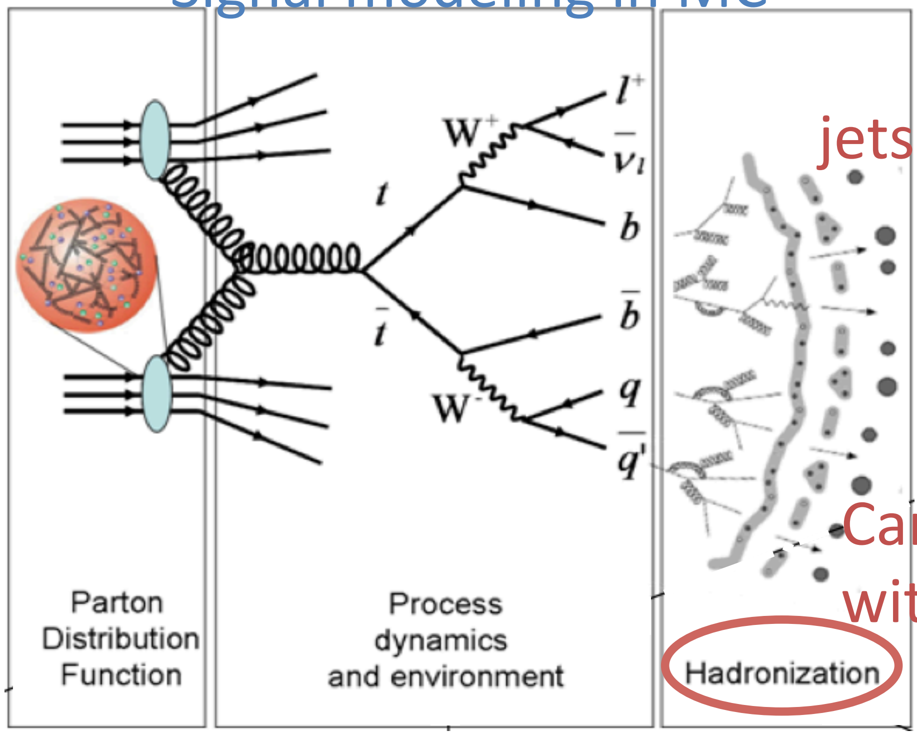
2. Weight function method

SK, Y.Shimizu, Y.Sumino, H.Yokoya, PLB 710, 658 (2012)
SK, Y.Shimizu, Y.Sumino, H.Yokoya, JHEP 08, 129 (2013)

New method for parent particle's mass reconstruction

- Only lepton energy distribution is needed
- Independent of top-quark velocity distribution

Signal modeling in MC



Cannot be treated within pert. QCD

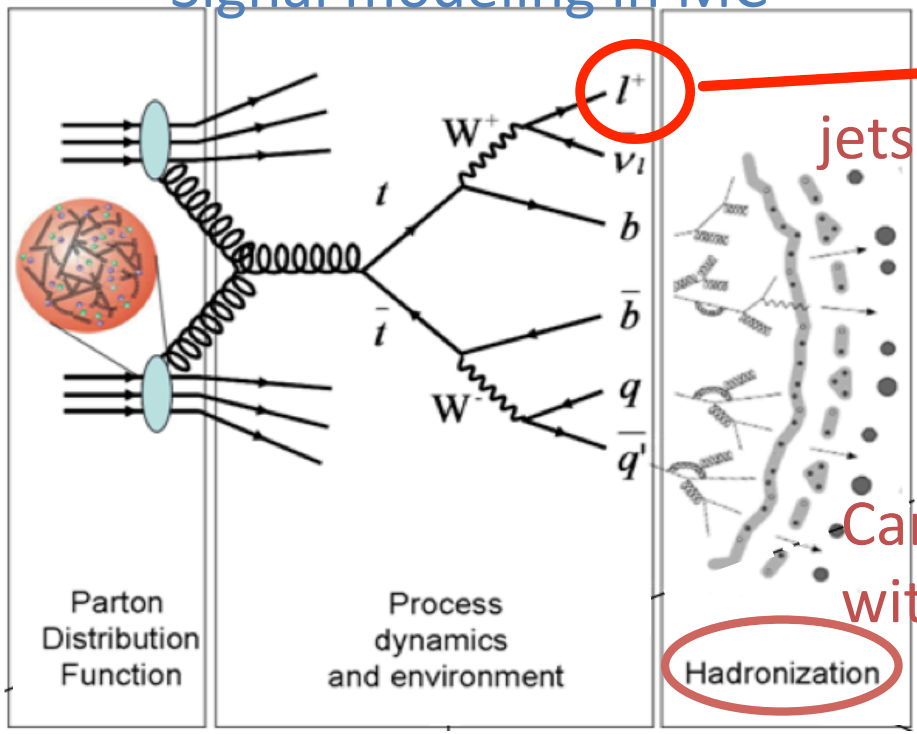
2. Weight function method

SK, Y.Shimizu, Y.Sumino, H.Yokoya, PLB 710, 658 (2012)
SK, Y.Shimizu, Y.Sumino, H.Yokoya, JHEP 08, 129 (2013)

New method for parent particle's mass reconstruction

- Only lepton energy distribution is needed
- Independent of top-quark velocity distribution

Signal modeling in MC



Free from ambiguity of hadronization model

We can determine a theoretically well-defined m_t

Cannot be treated within pert. QCD

Weight functions and the weighted integrals

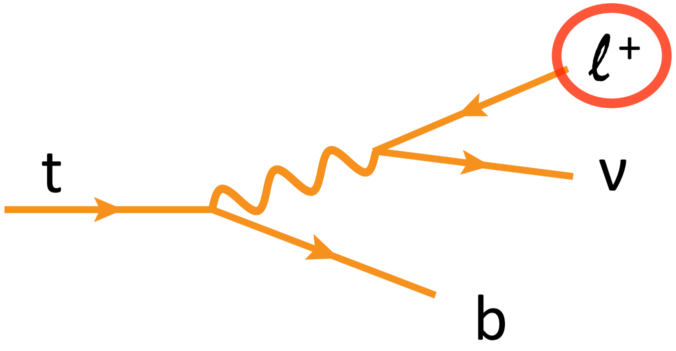
Weight function

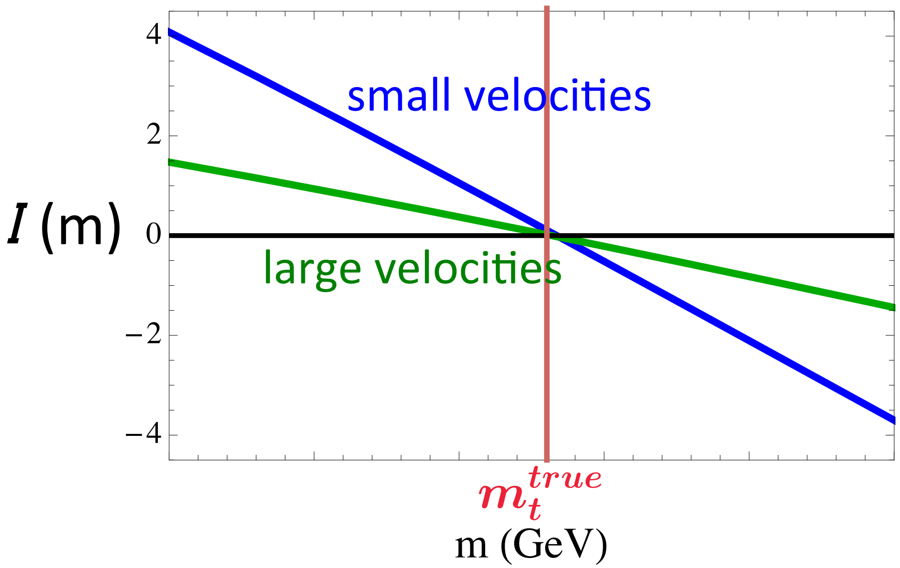
$$I(m) \equiv \int dE_l \, D(E_l) \, W(E_l, m)$$

Lepton energy distribution in the lab. frame

There exist an infinite number of weight functions which satisfy

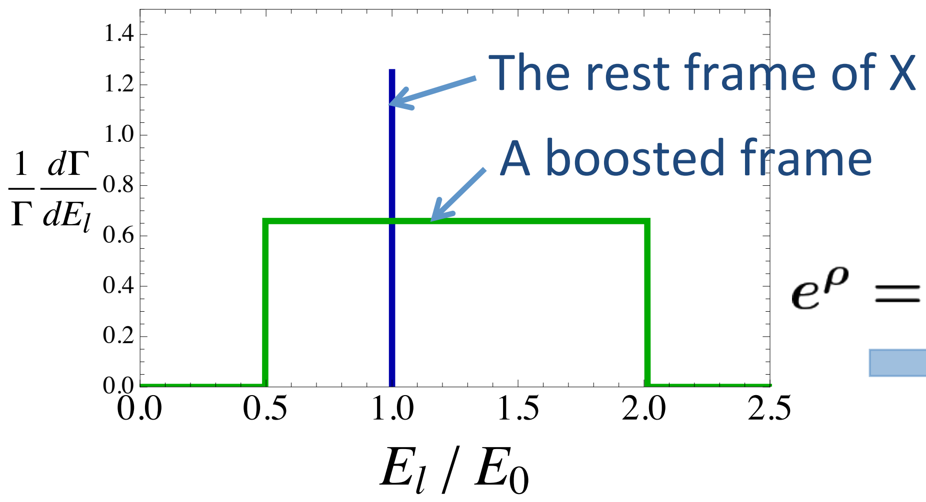
$I(m = m_t^{true}) = 0$ for an arbitrary velocity distribution of top quarks





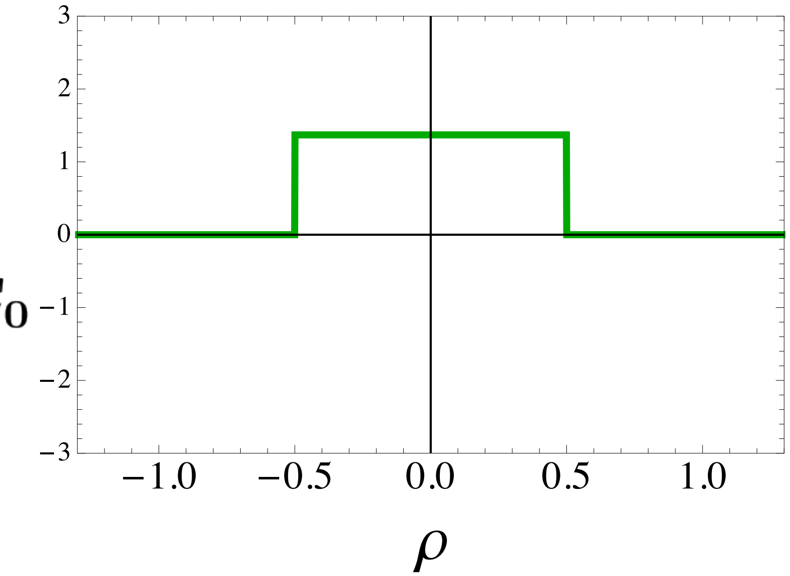
Construction of weight functions

For a two-body decay : X ⟶ ℓ + Y （X is scalar or unpolarized）



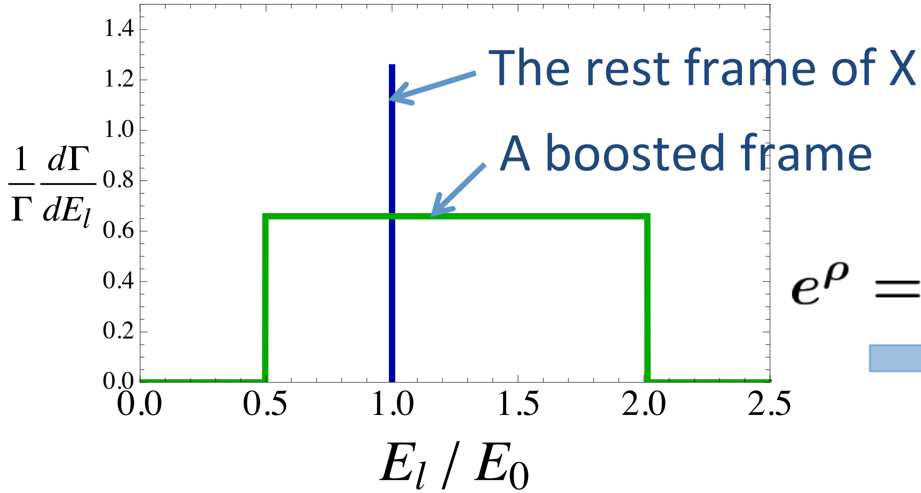
Lepton energy distribution

$$e^{\rho} = E_\ell / E_0$$



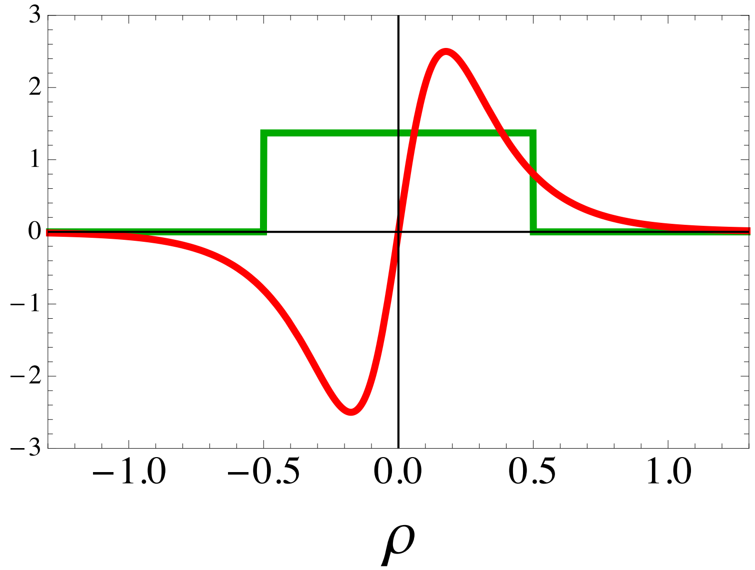
Construction of weight functions

For a two-body decay : X $\longrightarrow$ ℓ + Y （X is scalar or unpolarized）



Lepton energy distribution

$$e^{\rho} = E_\ell / E_0$$



$$\int dE_l\, D(E_l)\, W(E_l, m_X^{true}) = 0 \iff \int d\rho(\text{even func. of } \rho)(\text{odd func. of } \rho) = 0$$

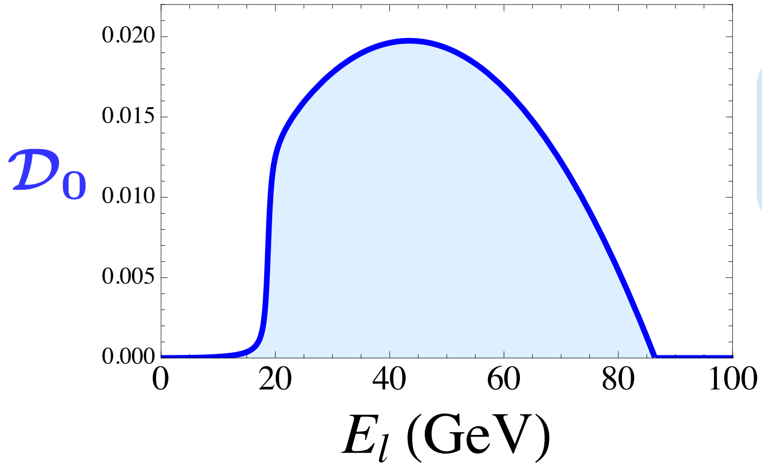
$$d\rho \propto e^{-\rho} dE_l$$

$$W(E_l, m_X^{true}) = \mathrm{e}^{-\rho}(\text{odd func. of } \rho)\big|_{\mathrm{e}^{\rho} = E_l/E_0}$$

Construction of weight functions

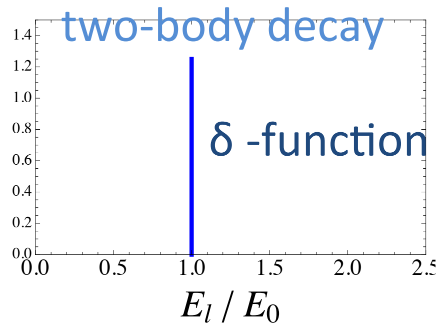
For a many-body decay : X $\longrightarrow \ell$ + anything (X is scalar or unpolarized)

Lepton energy distribution in the rest frame of X



Can be expressed as a superposition of lepton distribution for a two-body decay

$$\mathcal{D}_0(E_l) = \int dE\, \mathcal{D}_0(E)\, \delta(E_l - E)$$



A weight function would be also a superposition of that for a two-body decay

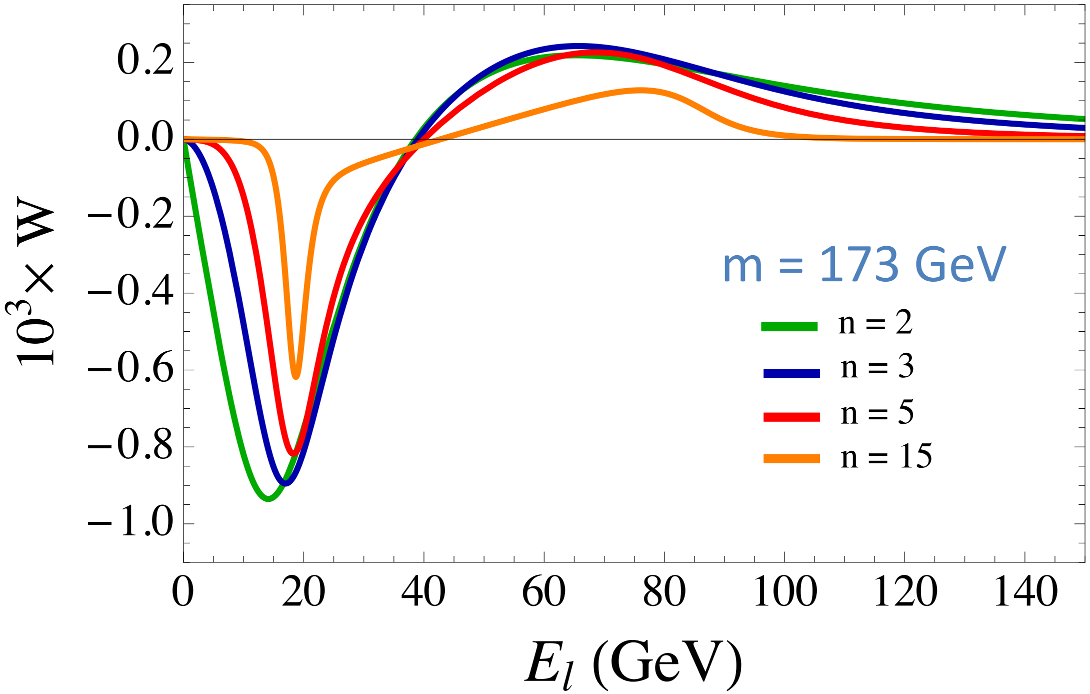
$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,; m) \frac{1}{E E_l} (\text{odd func. of } \rho) \Big|_{e^{\rho} = E_l / E}$$

Examples of weight functions

For a top quark decay : t → Wb → ℓ νb

$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,; m) \frac{1}{E E_l} (\text{odd func. of } \rho) \Big|_{e^{\rho} = E_l/E}$$

$$(\text{odd func. of } \rho) = \frac{n \tanh(n\rho)}{\cosh(n\rho)}$$



$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,; m) \frac{2n E_l^{n-1} E^{n-1} (E_l^{2n} - E^{2n})}{(E_l^{2n} + E^{2n})^2}$$

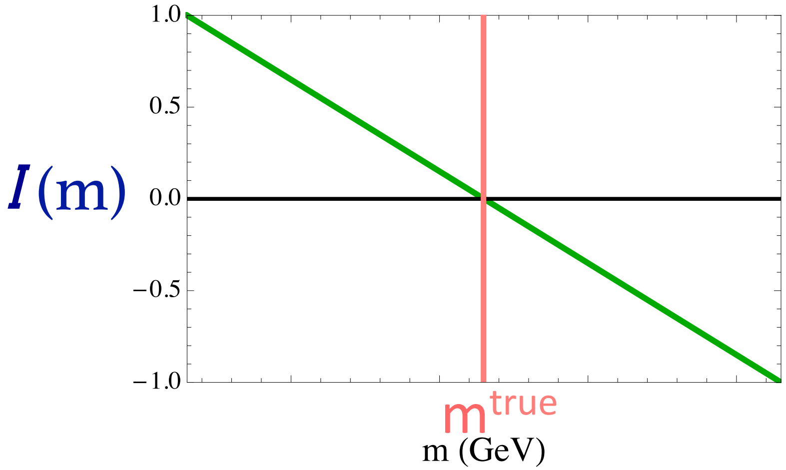
Summary of weight function method

1. Construct weight functions for the process

$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,; m) \frac{1}{E E_l} (\text{odd func. of } \rho)\Big|_{e^\rho = E_l/E}$$

Lepton energy dist. in the rest frame of parent particle, which can be calculated in pert. QCD

2. Use the lepton energy distribution measured by experiment as $D(E_\ell)$



$$I(m) \equiv \int dE_l D(E_l) W(E_l, m)$$

3. Obtain the zero of I (m) as m^{true}

$$I(m = m^{true}) = 0$$

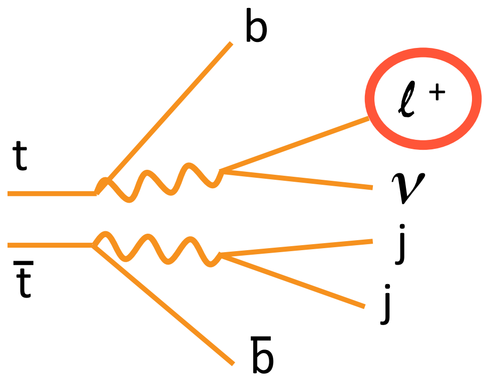
★ We can use this method if parent particle is scalar or unpolarized to determine any parameter which enters $\mathcal{D}_0$

3. Top mass reconstruction (Simulation analysis: LO)

Setup of the analysis

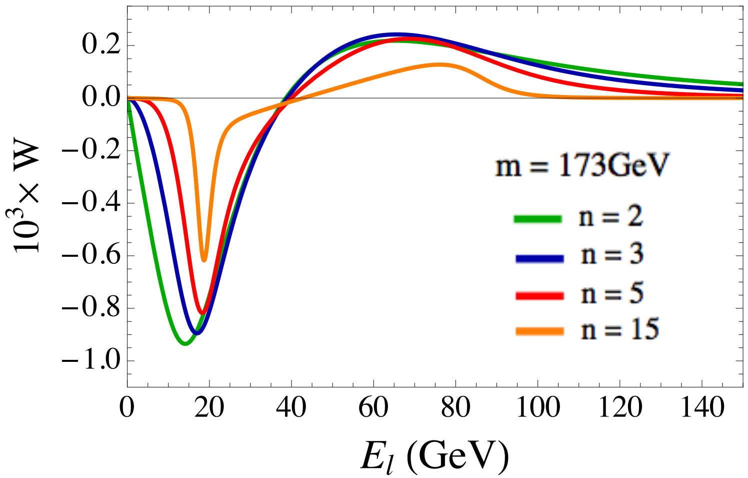
LHC $\sqrt{s}$ = 14 TeV

- Signal $t\bar{t}$ events, Lepton(μ)+jets channel



- Background Other $t\bar{t}$ events, W+jets, $Wb\bar{b}$+jets, Single-top production

- Weight functions used in this analysis

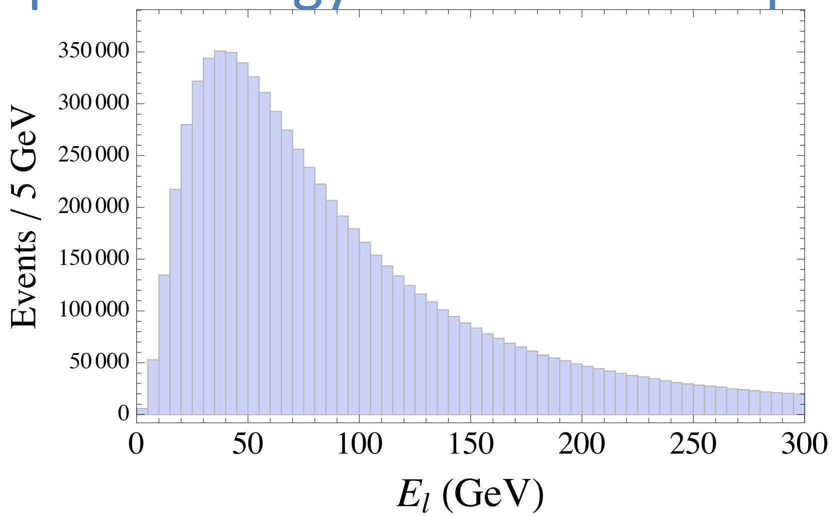


$$W(E_l, m) = \int dE\, \mathcal{D}_0(E\,;m) \frac{2nE_l^{n-1}E^{n-1}(E_l^{2n} - E^{2n})}{(E_l^{2n} + E^{2n})^2}$$

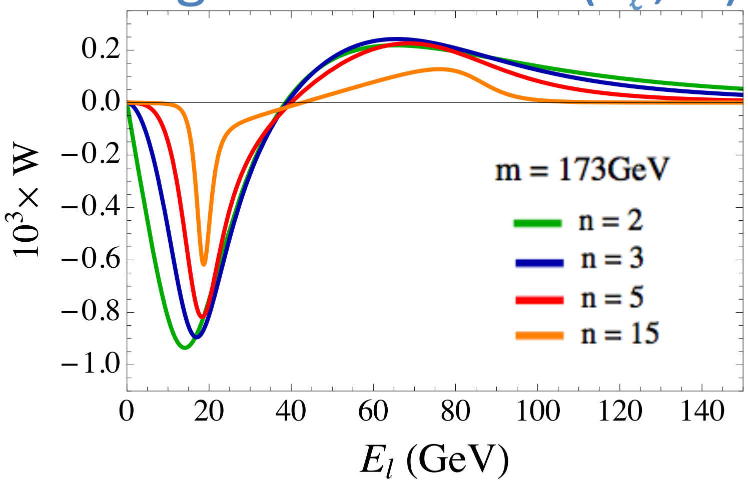
➡ Small weight at $E_\ell \sim 0$

Parton level analysis

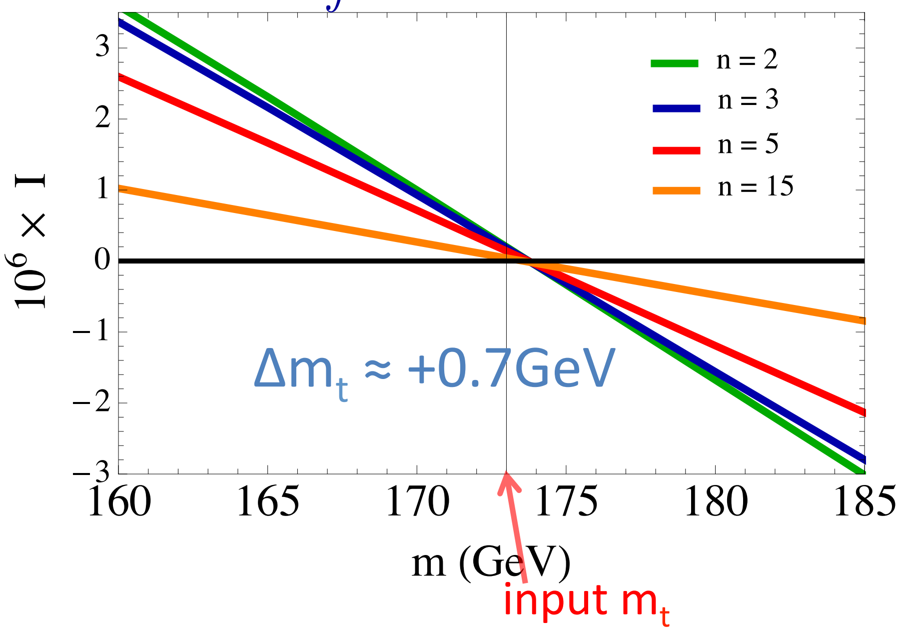
Lepton energy distribution at parton level (signal)



Weight function $W(E_\ell, m)$



$$I(m) \equiv \int dE_l D(E_l) W(E_l, m)$$



- Effect of Γ_t : +0.34GeV
- MC stat. error : 0.4GeV

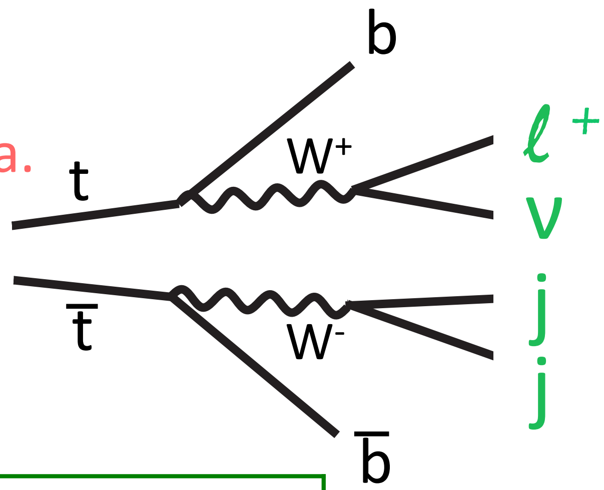
⇒ Consistent with expectation

In principle, our method works

Event selection cuts

- 1 muon with p_T > 20GeV, |η| < 2.4 (lepton cuts)
- At least 4 jets
- At least 1 b-tag with the b-tag efficiency 0.4 independent of p_T and η
- $p_T(j_1) > 55$, $p_T(j_2) > 25$, $p_T(j_3) > 15$, $p_T(j_4) > 8$GeV

We do not use cuts concerning missing momenta.



Cross section after all cuts

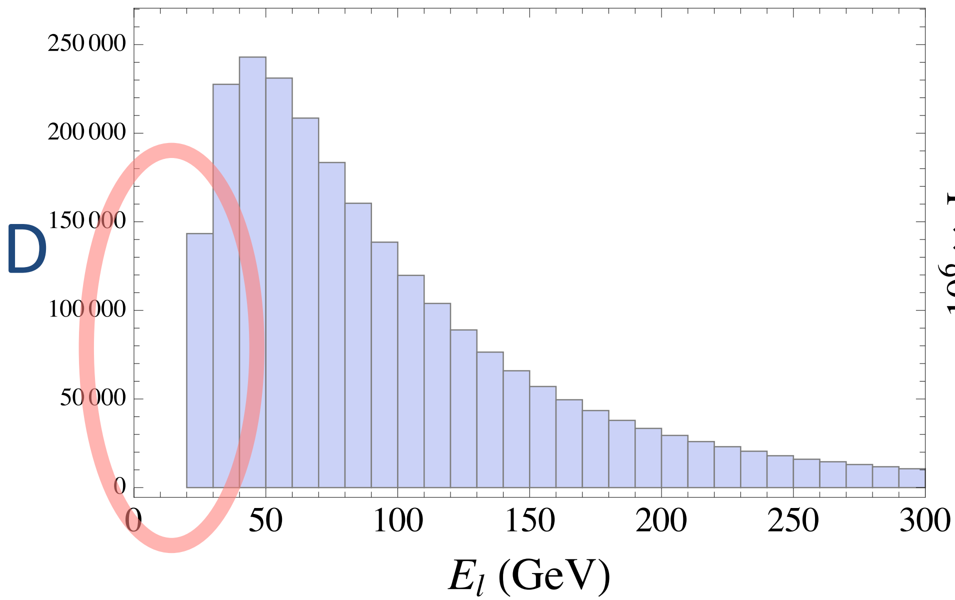
Signal (m_t=173GeV)	Other $t\bar{t}$ BG	W+jets BG	$Wb\bar{b}$+jets BG	Single top BG
22.4 pb	5.7 pb	1.8 pb	1.8 pb	1.3 pb

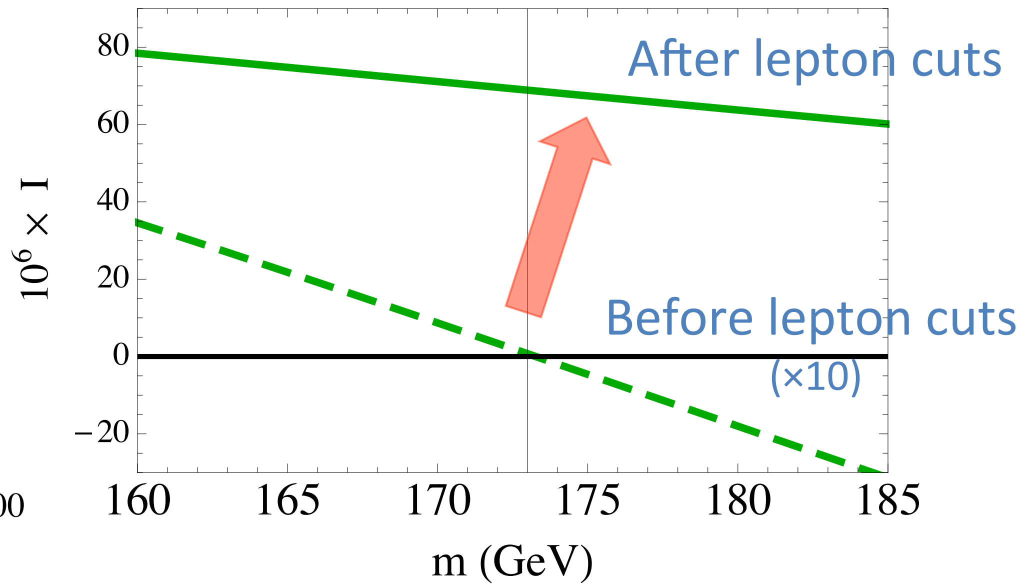
Effect of lepton cuts

The event selection cuts and backgrounds deform the lepton distribution.

The major effect is from the lepton cuts :

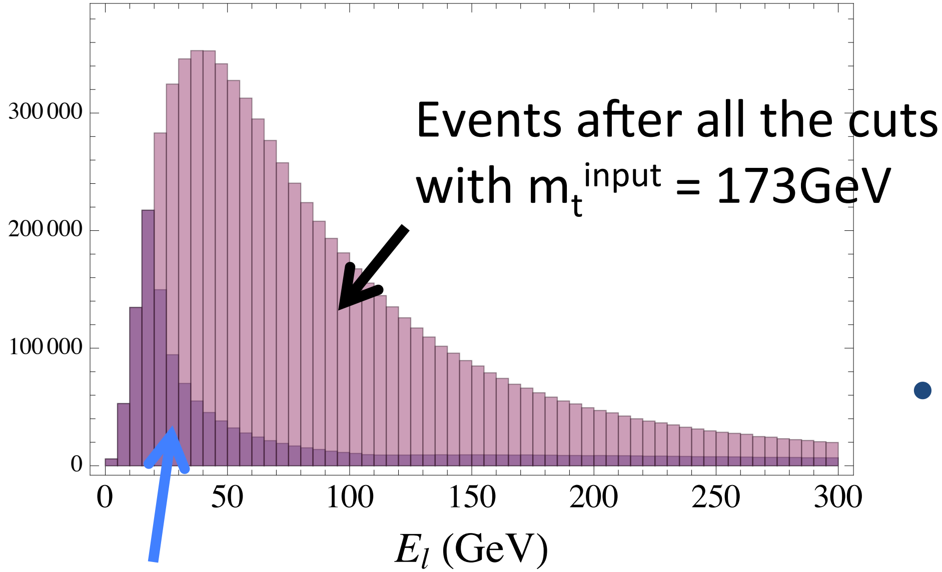
$p_T(\ell) > 20$ GeV, $|\eta(\ell)| < 2.4$



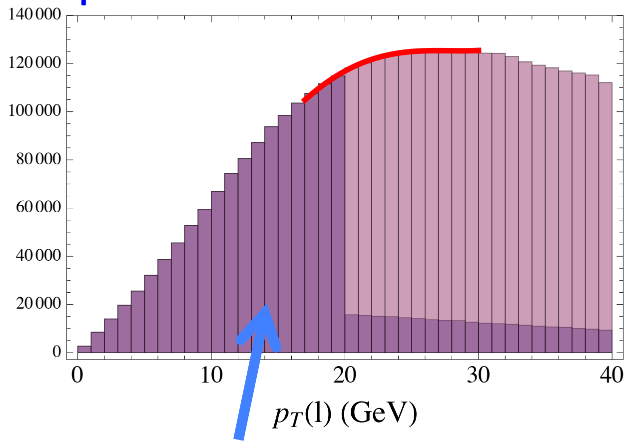


Solution to the problem of lepton cuts

We compensate for the loss using MC events.



Compensated MC events with m_t^c

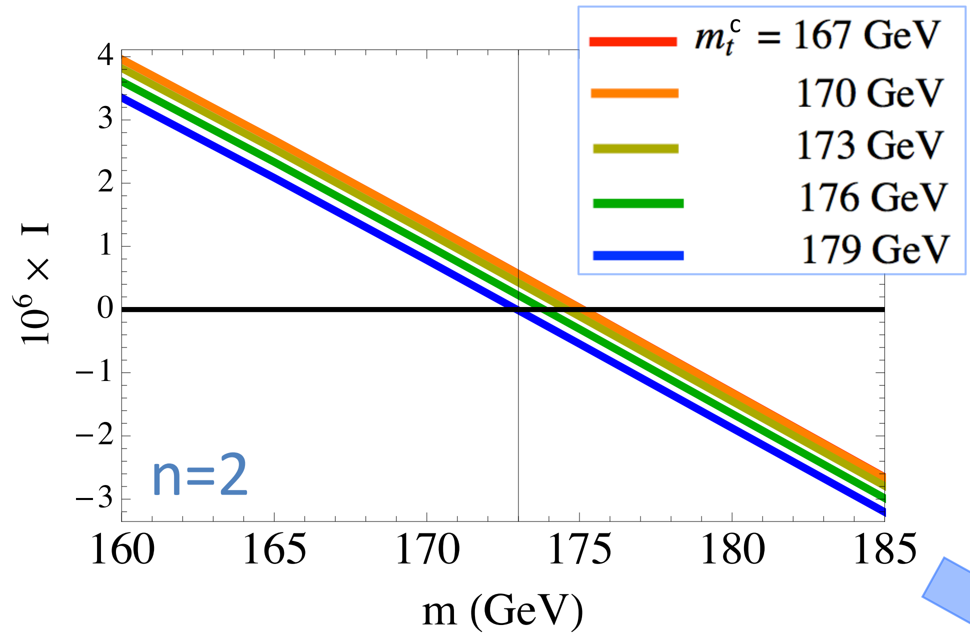


Compensated MC events

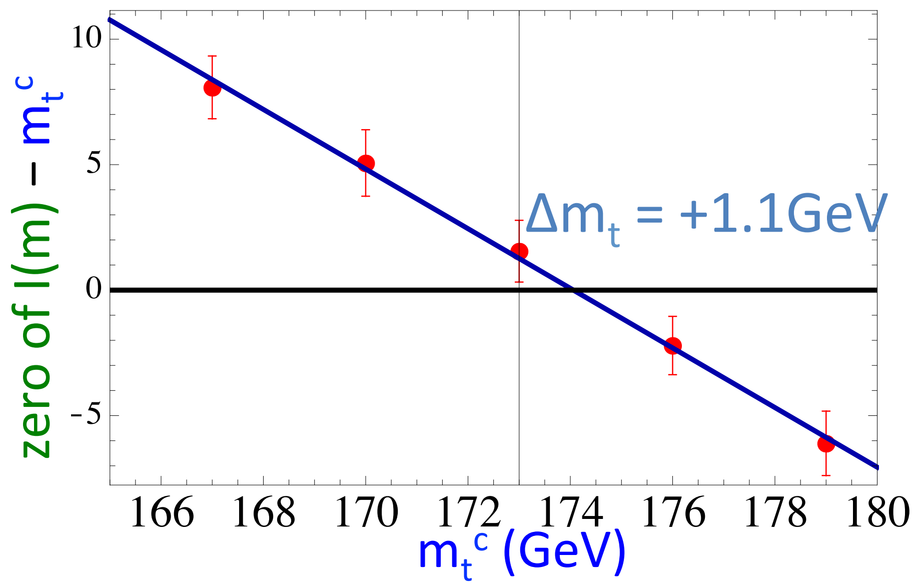
- We need to assume some value for m_t of the compensated MC events
- To fix the normalization of the added events, perform a χ^2-fit so that p_T(l) distributions are connected smoothly

Solution to the problem of lepton cuts

The weighted integrals with various m_t^c



The zeros of I(m) come close to the input mass (m_t^{input} = 173GeV)

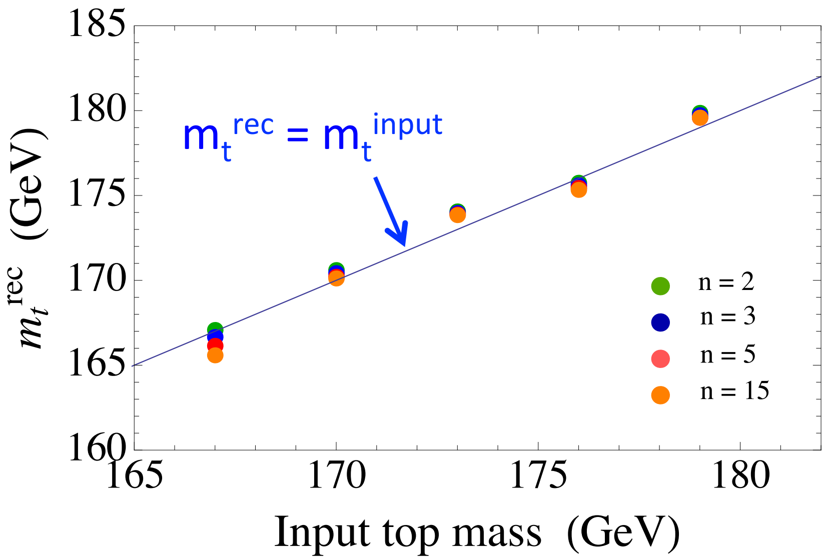


$m_t^c = m_t^{input}$ ⇒ zero of I(m) $= m_t^c$

$m_t^c \neq m_t^{input}$ ⇒ zero of I(m) $\neq m_t^c$ (guess)

Effect of Γ_t : +0.34GeV
MC stat. error : ~1GeV
⇒ Consistent

Sensitivity of m_t determination (LO)



n=2

Input top mass(GeV)	167	170	173	176	179
m_t^{rec}(GeV)	167.1	170.6	174.1	175.7	179.9

- At 100 fb^{-1}
- Lepton(e,μ)+jets channel
- Assuming that the error of electron mode is the same as the muon mode

Uncertainties [GeV]

	Signal stat. error	μ_F scale	PDF	JES	BG stat. error
n = 2	0.4	+1.5/-1.4	0.6	+0.5/-0.0	0.4
3	0.5	+1.4/-1.3	0.8	+0.7/-0.1	0.4
5	0.5	+1.4/-1.2	1.1	+0.8/-0.2	0.4
15	0.6	+1.4/-1.2	1.4	+0.9/-0.3	0.4

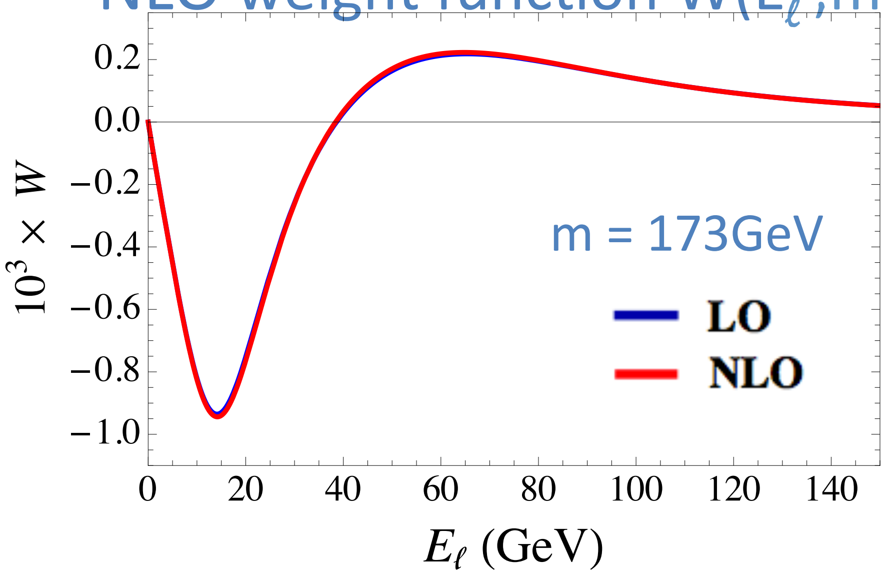
Can be improved by including NLO

NLO analysis (on-shell scheme)

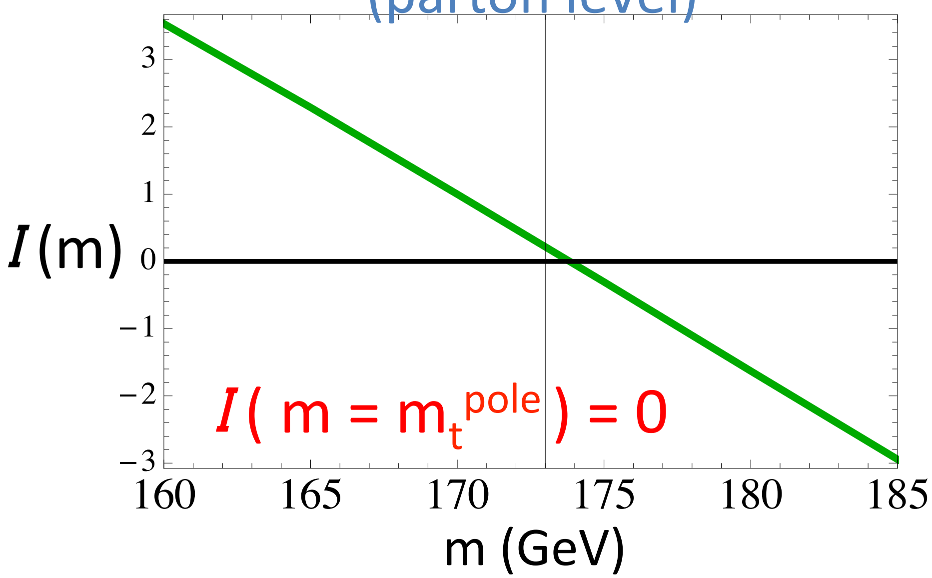
Required NLO correction

- involving only top production ➡ MC simulator
- involving only top decay ➡ MC + weight fn.
- involving both production and decay ➡ Correction

NLO weight function $W(E_\ell, m)$



簡易的simulation analysis (parton level)



4. Summary

- More precise measurements of m_t are needed.
- We proposed a new method to measure a theoretically well-defined top quark mass at LHC.
- We performed a simulation analysis of top mass reconstruction with lepton+jets channel at LO.
- The problem of the lepton cuts can be solved by compensating lepton distribution with MC events.
- The estimated stat. error is about 0.4GeV with $100 fb^{-1}$. Major systematic uncertainties are under good control.

Ongoing & future work

★ NLO, NNLO

- Include NLO, NNLO corrections to the top decay process in weight functions. ⇨ m_t^{pole}, $m_t^{\overline{MS}}$
- Include NLO corrections to the top production process in MC. ⇨ μ_F scale uncertainties can be reduced

★ Effects of top off-shellness

★ Collaboration with experimentalists

⇩

$m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV ⇨ We aim for $\Delta m_t^{pole} < 1$ GeV

ATLAS, Eur.Phys.J. C74, 3109 (2014)